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Determining the Effects of Microwave Power Variations on the Output Frequency of a High-Performance Cesium Frequency Standard

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Previous investigations of cesium (Cs) frequency standards demonstrated that Rabi pulling and cavity pulling were the most significant effects that translated microwave power variations into output frequency variations. It was also shown that there exist optimum values of the C-field that make the output frequency insensitive to variations in microwave power. Using a completely automated measurement system, we performed a similar study on a dual-beam, high-performance Cs frequency standard. The microwave power was precisely calibrated, and the effects of microwave cavity tuning on the output frequency were measured.

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PREFACE

The authors are grateful to Ronald L. Beard, Dr. Joe White, and Frederich Danzy of the Naval Research Laboratory for supplying the cesium frequency standard used in our studies.

CONTENTS

FIGURES

I. INTRODUCTION

Previous investigators presented experimental evidence [1,2], based on one manufacturer's cesium (Cs) frequency standards, confirming that Rabi pulling and cavity pulling are the major transducing effects that turn microwave power variations into output frequency variations. It was shown that there were C-field values for which the output frequency of the Cs standard is insensitive to changes in microwave power. In our earlier studies [3,4], we performed these C-field experiments on Cs clocks made by other manufacturers. We found C-field curves that were somewhat different from those found by the earlier investigators.

In this study we made C-field measurements on a Cs standard that was from the same manufacturer as the clocks measured by those earlier investigators. We should point out that this particular standard is an older model and may not be representative of the manufacturer's present design. We should also make clear that it is the only Cs standard from this manufacturer that we have measured at this time.

The C-field frequency dependence described in this report is for the sixth Cs standard measured in our laboratory. Previously we measured two standards each from two manufacturers and one from a third. The results presented herein are for a Cs standard from a fourth manufacturer. As in the case of the other manufacturers' standards, this standard also had to be modified to provide access to the microwave power and the C-field circuitry.

II. MEASUREMENT SYSTEM

Figure 1 is a block diagram of the complete measurement system. Measurements were automated to allow for the careful sequencing of data gathering without having to adjust or change any microwave connections manually. Both of the parameters that are varied, namely, the C-field current and the microwave power, are computer controlled; the current is set by a precision constant-current generator, and the microwave power is changed by a calibrated PIN diode attenuator. Good microwave matching at the 9.192-GHz interfaces into and out of the standard has been attained through the use of tuners and isolators at each interface. An amplifier has been added to compensate for the losses through the various components. The entire system is controlled by a Hewlett-Packard (HP) series 300 computer, which also acquires and processes the data.

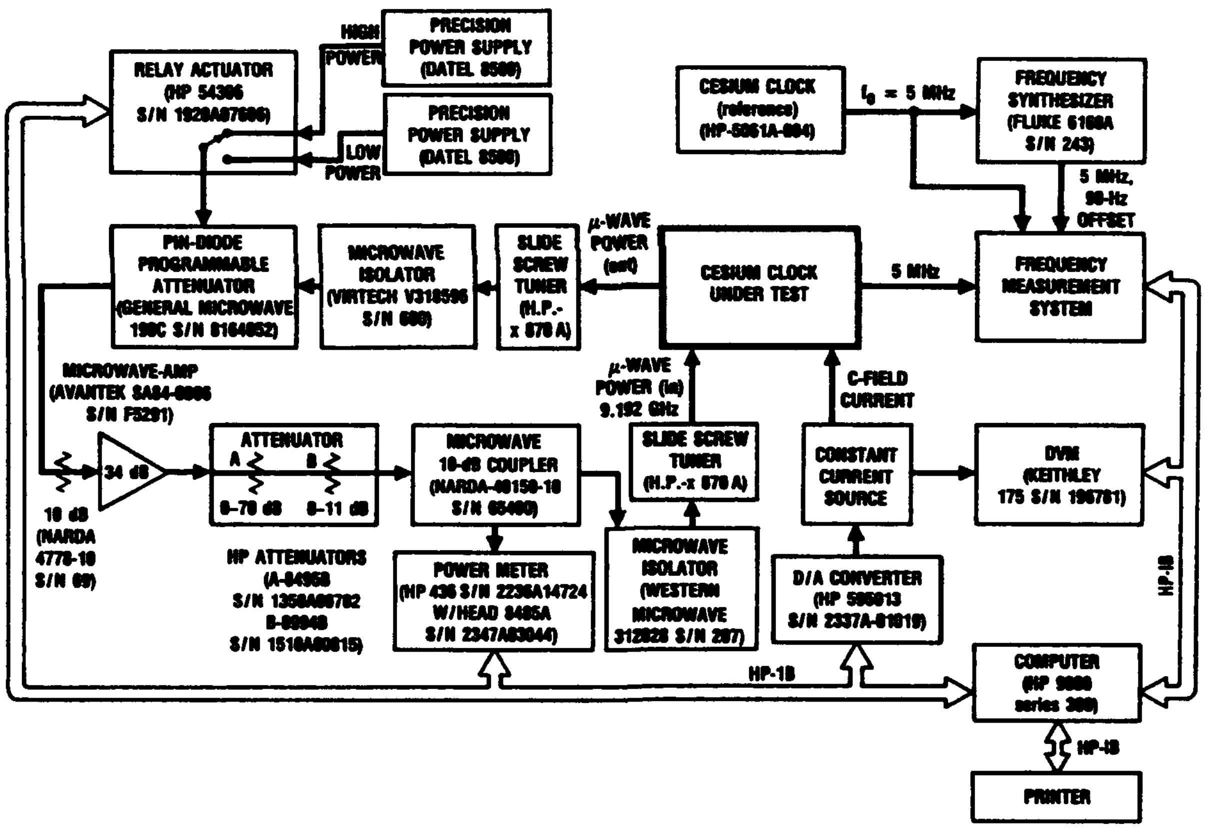

Figure 1. Block diagram of the C-field measurement system for a Cs frequency standard.

Figure 2 is a block diagram of the frequency measurement system. The frequency reference for both the Fluke synthesizer and the HP counter is an HP model 5061A-004 Cs frequency standard. Figure 3 shows a plot of the noise floor of the frequency measurement system and a plot of the frequency stability $\sigma_y(\tau)$ of the Cs standard used in our measurements with the HP frequency standard as the reference.

Before the data are taken, the microwave cavity of the Cs tube must be tuned. Figure 4 is a block diagram of the system that measures the return loss of the microwave cavity in the Cs tube. The microwave tuning is adjusted to obtain a maximum return loss at the resonant frequency f_0 of 9.192631770 GHz, as shown in Figure 5. The input microwave power is then adjusted to maximize the output current from the beam tube, as shown in Figure 6. The resulting microwave power is called the optimum power P_o.

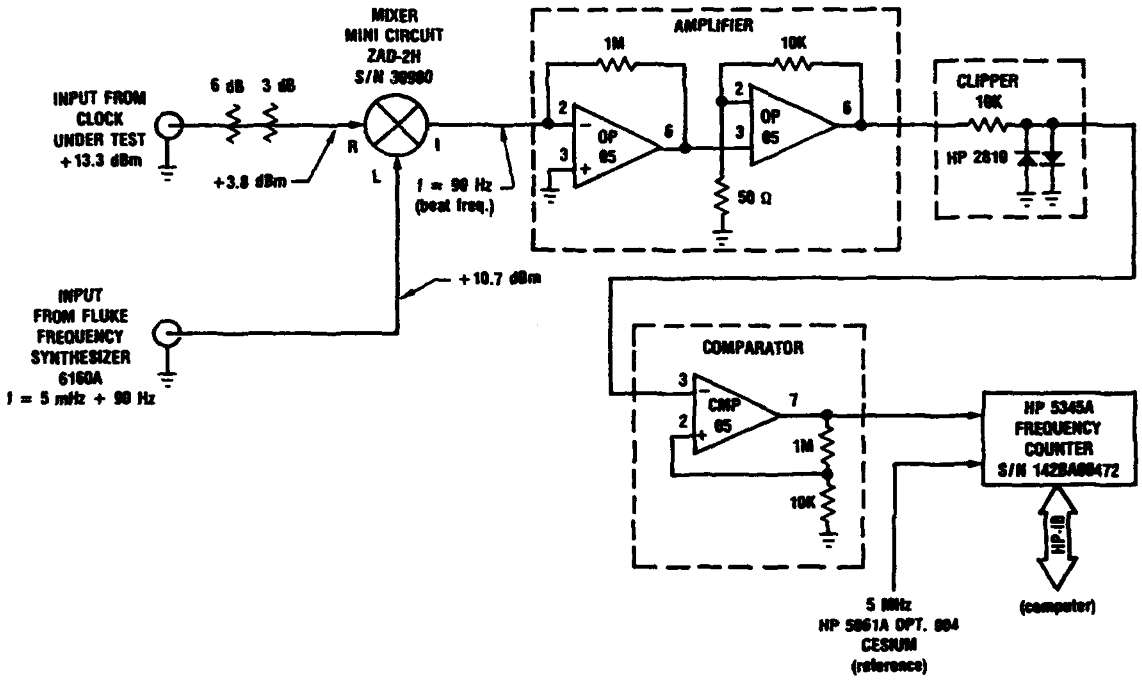

Figure 2. Circuit diagram of the single-mixer frequency-measurement system used to determine the fractional frequency changes at different C-field settings.

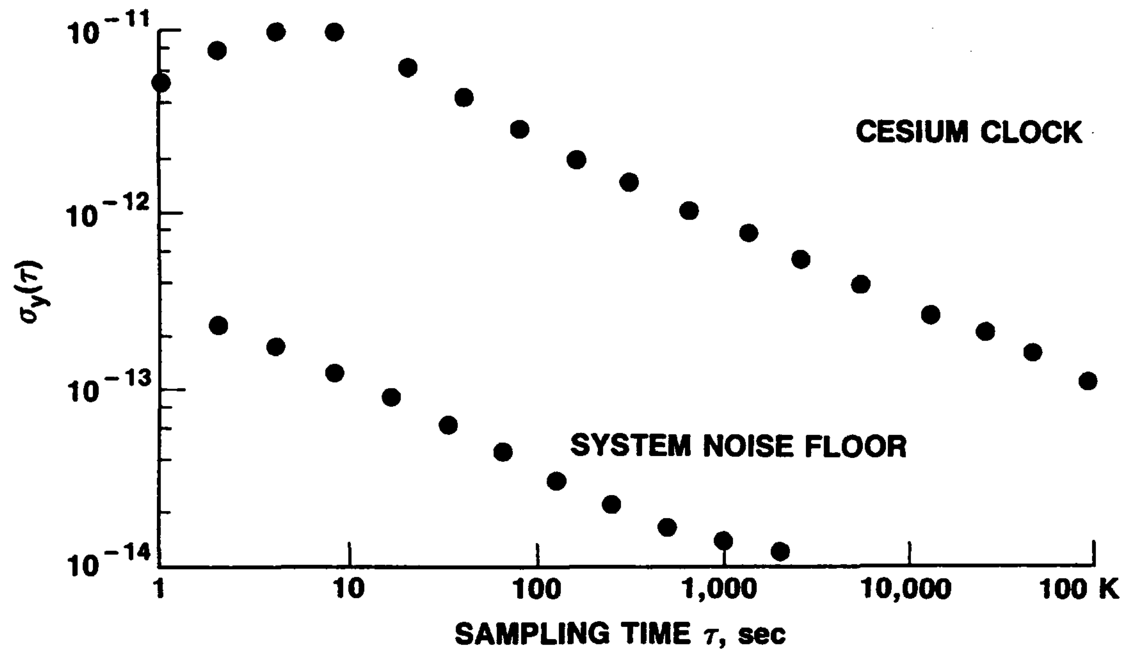

Figure 3. The measured square root of the Allan variance of the Cs frequency standard used in our measurements and the noise floor of the frequency measurement system.

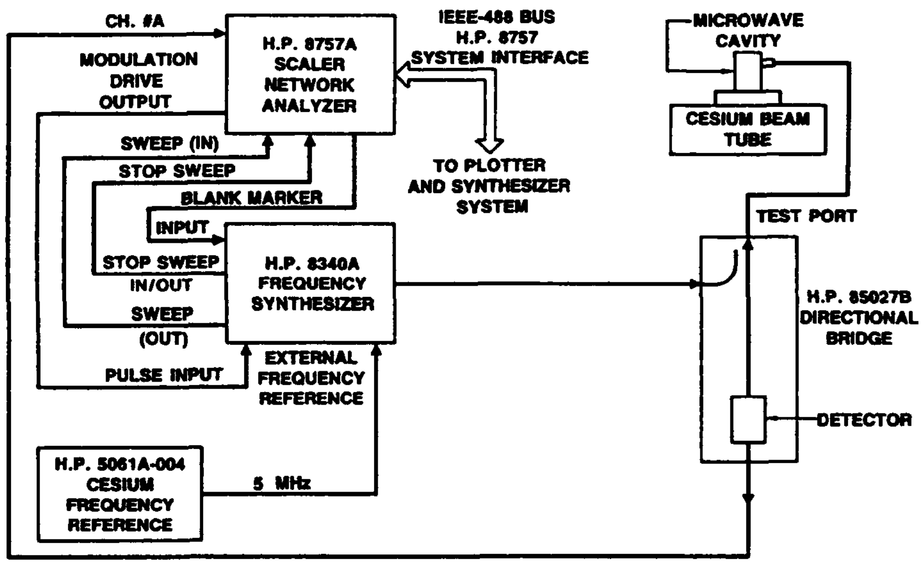

Figure 4. Block diagram of the Cs beam tube microwave-cavity measurement system.

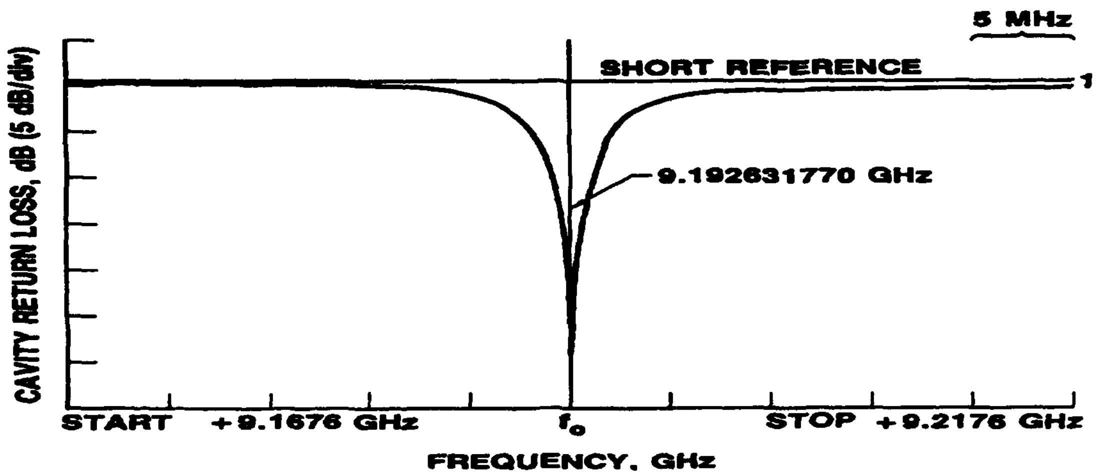

Figure 5. Plot of the microwave cavity return loss of the measured Cs frequency standard tuned to a Cs resonance frequency (f_0).

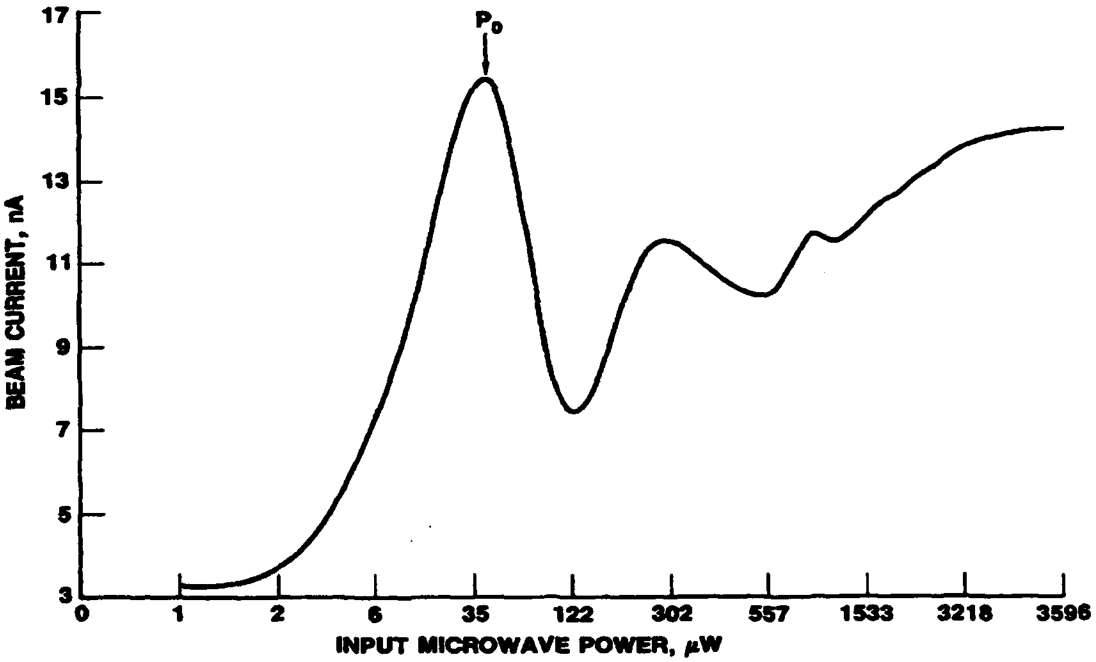

Figure 6. Plot of the Cs beam current vs. input microwave power of the Cs frequency standard tuned to f_0.

A typical data-taking sequence consists of the following steps:

1. Set the C-field current at some low value (typically from 6 to 8 mA) and the microwave power at some value (e.g., at the optimum value P_o).
2. Measure the beat frequency over some long averaging time T (typically 3000 sec).
3. Change the microwave power level (e.g., to $P_o + 1$ dB).
4. Measure the beat frequency over T again.
5. Increase the C-field current by some programmed amount (typically 0.5 mA).
6. Measure the beat frequency over T again.
7. Change the microwave power back to the initial value.
8. Repeat steps 2 through 7 until the final C-field current (typically 20 to 25 mA) is reached.

III. MEASUREMENT RESULTS

In order to plot the resulting C-field data as a function of the Zeeman frequency, measurements were made on the upper and lower microwave transitions to obtain the relationship between the Zeeman frequency f_Z and the applied C-field current I_C. A linear fit to the data yielded the relation

$$f_Z\ (\text{kHz}) = 0.115 + 3.300 \times I_C\ (\text{mA})$$

with a standard deviation of 29 Hz.

For each C-field current, a data point is calculated as the difference in beat frequency between the frequency at the higher power and that at the lower power, both of which are normalized to the nominal output frequency (5 MHz). In other words,

$$\text{ordinate} = (\bar{f}_H - \bar{f}_L)/5 \times 10^6$$

where $\bar{f}_H$ is the average beat frequency for the higher microwave power and $\bar{f}_H$ is the average output frequency for the lower microwave power. The reference frequency is set higher than the unknown frequency. Consequently, an increase in beat frequency corresponds to a reduction in the frequency of the standard being investigated.

Figure 7 is a plot of the average of the data runs on the standard after the tube's microwave cavity was tuned to f_0. Data were taken for power changes of both +1 dB and +3 dB above P_o. For the +1-dB data, each and every frequency measurement was averaged for a time that ranged from 17,300 to 45,300 sec, depending on the data point. The associated standard deviations were between 2.7 and 1.7×10^{-13}. For the +3-dB data, each frequency measurement was averaged for a time that ranged from 7,000 to 9,000 sec, again depending on the data point. The standard deviations in this case are between 4.2 and 3.7×10^{-13}.

The +1-dB data shown in Figure 7 exhibit a zero crossing at about 25 kHz and a maximum $\Delta f/f_0$ of about 1.7×10^{-12} at 31 kHz. For the +3-dB data, there is a zero crossing near 26 kHz and possibly one at about 45 kHz; the maximum $\Delta f/f_0$ of 5.7×10^{-12} also occurs at 31 kHz. The frequency offset tends to decrease as the Zeeman frequency (and, hence, the resonance-line separation) increases. These results are similar to those found in our earlier studies [3,4] on Cs standards made by other manufacturers.

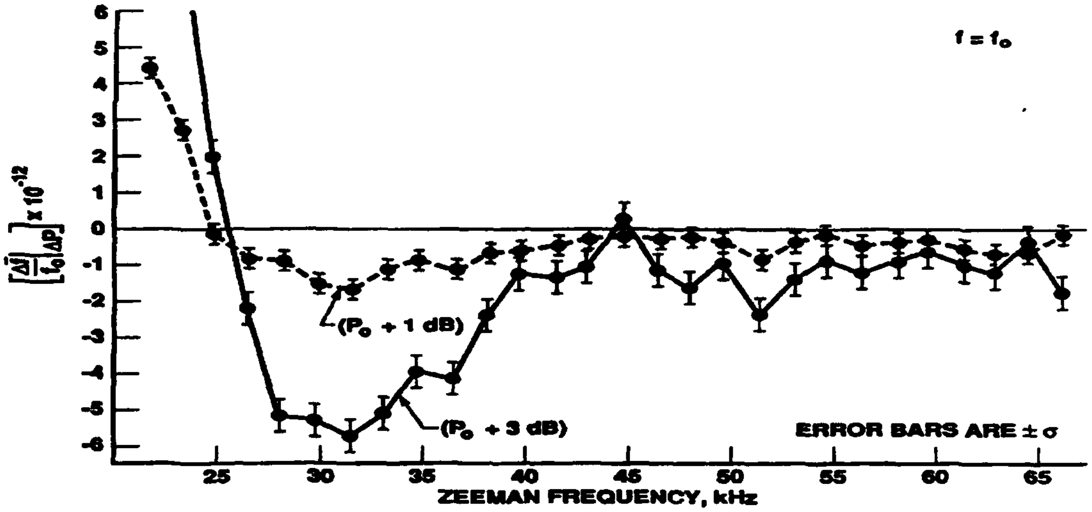

Figure 7. Average of final data regarding the difference of the average frequencies as a function of C-field for a microwave power change of +1 and +3 dB above the optimum power level P_0.

The effect of cavity pulling on the C-field frequency dependence was also measured. Using the test setup depicted schematically in Figure 4 to measure return loss, we varied the slide-screw tuner until the tuner and tube were tuned to 5 MHz above f_0. The shape of the return-loss curve was essentially identical to that of Figure 5, except that the maximum return loss was at f_0 + 5 MHz. The C-field data were then taken for a power change of +3 dB. Then the cavity was tuned to 5 MHz below f_0, and the measurements were repeated. The results are shown in Figure 8. The averaging times T ranged between 6,000 and 9,000 sec, and the standard deviations were between 4.6 and 3.7 x 10^{-13}.

The collapse of the frequency offsets is interesting and is entirely consistent with the predictions for a monovelocity beam. The 5-MHz cavity offset caused a 6-dB reduction in cavity microwave power. This should reduce the magnitude of the measured Rabi pulling by a factor of 18 and the cavity pulling by a factor of 7. We raised the microwave power level by 6 dB and repeated the measurement for a power change of +3 dB, while maintaining the cavity offset at 5 MHz. We recovered the original Rabi pulling seen in Figure 7 and acquired a cavity pulling of 1 x 10^{-12}. This corresponds to a coefficient of about 1.5 x 10^{-13} per dB per MHz under the original conditions of P_0 and zero cavity offset.

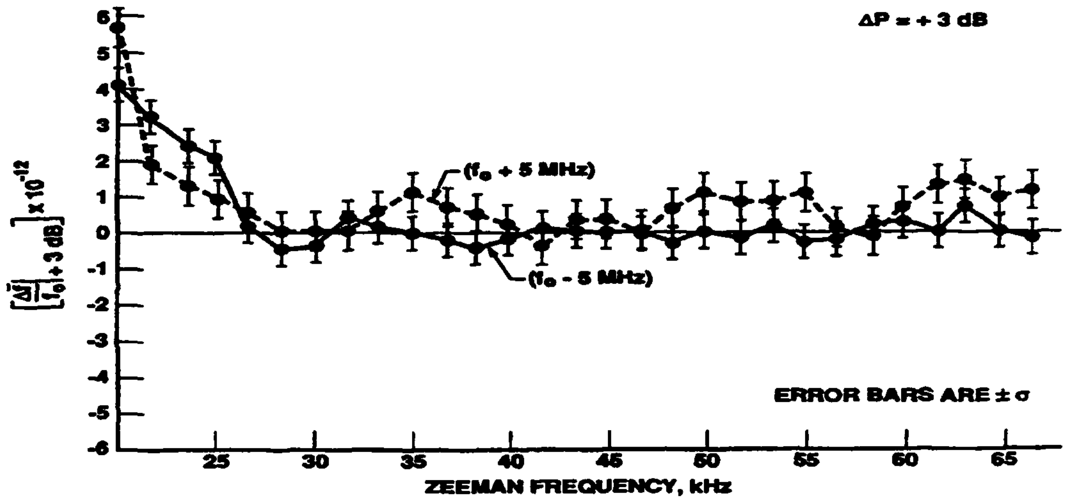

Figure 8. Plot of the difference of the average frequencies as a function of the C-field of the Cs frequency standard for two microwave cavity tuned frequencies (f_0 and ± 5 MHz) for a microwave power change of + 3 dB above the optimum power level P_o.

IV. INACCURACIES IN THE MEASUREMENT SYSTEM

Our measurement system introduces three sources of error or uncertainty: (1) frequency measurement noise, (2) C-field current setting errors, and (3) microwave-power measurement errors. The first source of uncertainty has been shown (see Figure 3) to be almost two orders of magnitude below the standard deviation of the data. The second source of uncertainty is probably on the order of parts in 10^4 in our laboratory environment over the 3 months during which data were taken; this stability is largely set by the stability of a precision film resistor. The third source of uncertainty is the most difficult of the three sources to assess. For a microwave source and measurement system that is very similar to that of Figure 1, it was found [5] that the standard deviation of microwave power was between 0.04 and 0.06 dB for measurement intervals between 0.14 and 2.5 days. In addition, the drifts in the power measurement system (consisting of the power meter, the power measurement head, and the calibrator) were examined separately. In two long runs of 10 and 16 days each, these drifts were found to have power-measurement standard deviations of 0.0012 and 0.0025 dB, respectively.

V. CONCLUSIONS

This report has presented the results of a measurement of the sensitivity of output frequency to variations in microwave power, as a function of C-field, on a particular Cs frequency standard. Although this standard may not necessarily reflect the manufacturer's most current technology, it is nevertheless a high-performance unit. The results showed that Rabi pulling in this standard was similar to the offsets we measured in our laboratory on other Cs standards from different manufacturers. In particular, the Rabi pulling becomes extremely small in the vicinity of 45 kHz and remains less than 1×10^{-12} per dB for higher Zeeman frequencies. In addition, we estimate the cavity pulling at optimum power to be 1.5×10^{-13} per dB per MHz offset.

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